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Report of the Results of the Vehicle Surveillance Program 14

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LISTS OF ABBREVIATIONS

ARB	California Air Resources Board.
ASM	Acceleration Simulation Mode. Constant speed tests run at 50 percent power and 15 mph (“5015”) or 25 percent power and 25 mph (“2525”).
BAR	Bureau of Automotive Repair. Sometimes a reference to the Smog Check Program.
CEE	California Environmental Engineering, the vehicle procurement contractor.
CO	Carbon monoxide, a criteria pollutant.
CVS	Constant Volume Sampler, as used in CVS-75 test, the Federal Test Procedure.
EGR	Exhaust Gas Recirculation, an emissions control system for NOx.
FTP	Federal Test Procedure, the official U.S. EPA dynamometer test for new vehicle certification.
HC	Hydrocarbons. Regulated as ozone precursors.
I/M	Inspection and Maintenance.
LEV	Low Emission Vehicle. A vehicle that meets the tightened California standards adopted in 1990.
MVDAS	Motor Vehicle Data Acquisition System, the ARB’s computer system used to conduct dynamometer tests and to acquire associated test results.
NO_x	Oxides of nitrogen. Regulated as ozone precursors. NO is harmless, while NO_2 is a criteria pollutant and causes respiratory damage.
OBD	On-Board Diagnostics.
PCV	Positive Crankcase Ventilation, an emissions control for blowby hydrocarbons.
SHED	Sealed Housing for Evaporative Determination, a test method to quantify fuel evaporative emissions.

SFTP	Supplemental Federal Test Procedure, which includes simulated aggressive driving cycles and simulated air conditioning use
TAC	Thermostatic air cleaner, the system used to heat incoming air upon vehicle start-up during cold engine conditions.
TAS	Test Analyzer System, vehicle exhaust analytical equipment used for Smog Check I (i.e., BAR-84 and BAR-90 I/M programs).
UC	Unified Cycle. A second-generation driving cycle designed to more realistically simulate California driving.
UCC	Unified Correction Cycles. Research cycles to develop correction factors for various speeds.
ULEV	Ultra Low Emission Vehicle.
VC	Vehicle check-in function of the ARB.
VDAR	Vehicle Diagnostic and Repair Section.
VEDS	Vehicle Emission Database System, the ARB's vehicle emission database.
VSP	Vehicle Surveillance Program.
VSS	Vehicle Surveillance Section.

EXECUTIVE SUMMARY

The purpose of all Vehicle Surveillance Programs (VSPs) has been to take periodic measurements of a representative sample of the California fleet of in-use vehicles. Data are used to support the mobile source emissions inventory, to measure the effectiveness of the inspection and maintenance (I/M) program procedures, and to monitor the life and effectiveness of emissions control equipment, among other uses. The fourteenth Vehicle Surveillance Program (VSP 14) was conducted from November 1997 to August 1999, and tested 332 vehicles. Vehicles were chosen randomly by vehicle identification number patterns from registered owners living within a 25-mile radius of the Air Resources Board's test facility in El Monte. Selected vehicle owners were offered $150 to $200 and the use of a rental car for their participation.

Compared to the California fleet, the VSP 14 was older, on average (12.7 years versus 11.8 years for VSP 13), and included fewer new vehicles, but had a similar span of model years and a roughly similar distribution of age overall. The rate of participation among owners randomly chosen was about 10 percent. This was slightly lower than the previous two programs. The primary obstacle to obtaining a higher capture rate was the difficulty in reaching prospective owners by telephone (due to unlisted, inaccurate, or out-of-date numbers). Potential biases due to the low participation rate and the selection process should be further investigated, as described in this report.

Once obtained for testing, vehicles were first given a simulated Smog Check II I/M inspection, which included a visual and functional check of the vehicle's emissions control equipment, and emissions tests using a dynamometer. Dynamometer tests were similar to those required by Smog Check II in areas of California not meeting federal air quality standards (the ASM 2525 and ASM 5015 Tests). In addition to the simulated Smog Check II, emissions were tested using the variable-speed dynamometer tests used to certify new vehicles (the CVS Test using the FTP Cycle), and the variable-speed test designed to more closely simulate driving in urban areas (the Unified Cycle Test).

Vehicles not passing the visual or functional inspection criteria, or failing the ASM standards were repaired, and all testing was repeated. This cycle was repeated until a vehicle passed all inspection criteria and ASM standards or could not be further improved.

Results of the VSP 14 emissions testing program showed very good agreement between the steady-state ASM 5015 and ASM 2525 Tests, and between the variable-speed CVS and the UC Tests, although the 5015 and UC Tests on average showed slightly higher emissions. All tests showed the same basic trend of roughly linear increases in emissions starting at about 30,000 to 50,000 miles, and at 6 to 8 years of age. The overall average CVS emissions for the VSP sample before repairs was about 1.9 gram per mile hydrocarbons, 20 grams per mile CO, and 1.4 grams per mile NOx. These results closely match the average emissions of the previous VSP 13.

VSP 14 found much higher visual and functional failure rates (34 percent and 41 percent, respectively) with its simulated I/M tests than California's official Smog Check II (5 percent and 2 percent, respectively). The reason for this difference is not known. Similar to previous VSPs, high rates of tampering were also observed, tampering defined as any part of the emissions control system removed, disconnected, or modified. In VSP 14, 31 percent of the vehicles were considered tampered. Of all repairs made in VSP 14, 25 percent were performed to fix tampered control systems or components. Overall, 62 percent of VSP 14 vehicles were repaired. (This overall failure rate is not directly comparable to overall Smog Check II failure rates of about 10 percent because stricter ASM criteria were used by the ARB than Smog Check II.)

The average cost per repaired vehicle in VSP 14 was $259, including labor at $50 per hour. The average cost per vehicle for all vehicles was $150, higher than the recent Smog Check II average of $100. However, because the Smog Check II has a much lower failure rate, the average cost of repairs for those fewer failing vehicles was several times higher than VSP 14, i.e., closer to $1000 per repaired vehicle.

Repairs reduced emissions from the repaired vehicles by 50 percent to 70 percent for the ASM Tests, 35 percent to 40 percent for the CVS Test, and 20 percent to 50 percent for the UC Test, depending on the pollutant. Generally, reductions were higher for HC and CO than NOx. Absolute emissions reductions increased with higher odometer readings, but proportionally, emissions reductions were roughly constant across vehicle odometer readings. By vehicle model year, however, the greatest reductions were seen for the middle-aged vehicles of the 1975 to 1988 model years, or vehicles roughly 10 to 23 years old. Both newer and older vehicles had significantly lower emissions reductions after repairs.

INTRODUCTION

The key objective of the Vehicle Surveillance Section (VSS) is to take periodic "snapshots" of statewide vehicle fleet emissions. This is done by taking a representative sample of in-use vehicles and testing them at the Air Resources Board's (ARB's) El Monte facility. The primary use of these results is to provide the data used by the on-road mobile source model, which calculates the on-road portion of the mobile source emissions inventory. Vehicle testing results are also used to support the establishing and evaluation of regulatory standards and the development of emissions control programs, including:

1. Evaluating the cost-effectiveness and overall effectiveness of the Smog Check II Inspection and Maintenance (I/M) Program.
2. Gathering information on rates of deterioration, maladjustment, and tampering of emission control equipment on vehicles currently in use.
3. Evaluating evaporative emissions from parked vehicles, in both hot and cooled-down states.
4. Gathering chemical-by-chemical (speciated) profiles of vehicle exhaust and evaporative emissions.
5. Evaluating various driving simulation cycles.

Vehicle testing at the ARB is organized into Vehicle Surveillance Programs (VSPs). Each Program tests several hundred vehicles, and lasts one to two years. Program 14 (VSP 14), the subject of this report, tested 332 vehicles and was conducted from November 1997 through August 1999. These vehicles were chosen at random, in groups of similar manufacturer, year, and engine type, from addresses within a 25-mile radius of the El Monte facility.

In VSP 14, a comprehensive series of tests was conducted on each vehicle, including a simulated Smog Check II I/M procedure, supplementary I/M tests, simulated driving cycles on dynamometers, and evaporative tests of parked vehicles. Vehicles that did not pass I/M criteria were repaired and re-tested; a process that was repeated until a vehicle passed all criteria. These procedures took anywhere from three days to several weeks, depending on the extent of repairs required. (Most of the simulated driving cycles require starting the test with a cold engine, so generally only one test per day could be performed.)

VEHICLE PROCUREMENT

The Procurement Process

Similar to previous VSPs, VSP 14 attempted to obtain a sample of vehicles which was representative of the composition of the statewide fleet by vehicle and engine type. To accomplish this, a random sample of vehicles was first taken from registration records maintained by the California Department of Motor Vehicles (DMV). From this random sample, vehicle identification numbers (VINs) were condensed into VIN "patterns" which specified manufacturer, model, year, and engine type. For each VIN pattern created, lists of owners who matched this pattern and who lived within a 25-mile radius of the ARB in El Monte were generated randomly. These lists were supplied to a contractor, California Environmental Engineering (CEE) of Santa Ana, who assumed responsibility for contacting and recruiting participants and delivering their vehicles to the ARB.

For each VIN pattern, CEE attempted to recruit participants by mail and telephone contact. For each potential participant, up to three mailings and six telephone calls were made. Daytime, evening, and weekend telephone calls were all made. Prospective owners were offered a cash incentive of $150 to $200, along with a free tank of gas, a wash and wax, and the possibility of free repairs to their emission control systems.

CEE attempted to procure the vehicle for each VIN pattern in rank order, beginning with the top of each list. To ensure complete randomness and no bias (bias due to refusal to participate), the first person on each VIN pattern list would have had to agree to participate. In actuality, the participants averaged about eighth in rank, so the possibility existed that participating owners and their vehicles differed from those who refused to participate. For example, owners of well-maintained vehicles may have been less likely to give up their vehicle than owners of poorly maintained vehicles. This is a concern that should be addressed in future studies[1].

Acceptance Criteria and Possible Sample Biases

As in previous VSPs, not every willing participant provided a testable vehicle. Only vehicles with current registration were acceptable (for legal reasons), and vehicles had to be not only roadworthy but testable on the dynamometer as well. Of vehicles meeting these criteria, 27 vehicles (about 8 percent of the sample) were rejected by the ARB after procurement by CEE. The major reasons why a roadworthy vehicle was not testable were:

- excessive smoking or unfixable exhaust leaks (7);
- dynamometer incompatibility reasons (large vehicle size, four-wheel drive only, window or door problems preventing access to dyno controls) (4);
- engine problems (knocking) (3);
- transmission and shifting problems (3);
- unsafe to test (steering problems, sparking) (2);
- overall poor condition of vehicle (3);
- wrong category of vehicle (2); and
- other (3)

If any testability problems could be fixed without changing the vehicle's emissions, these fixes were typically performed, such as brake repairs. Every effort was made to test each vehicle procured in the program so as to minimize the bias towards better-performing vehicles in the sample. However, because most of the 27 non-testable vehicles were in worse condition than the testable vehicles, they most likely had higher emissions than comparable vehicles in normal condition. Therefore, dynamometer testability requirements likely introduced a slight bias towards vehicles in better condition.

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[1] The questionnaire used in the following program, VSP 15, was re-designed to gather the information necessary to evaluate this possible non-participation bias, a type of "non-response bias," as it is termed in the field of survey science.

Another significant change in VSP 15 is that it ended the use of VIN patterns in the procurement process. Instead, participants were recruited from a single, randomly-selected pool of owners. This eliminated a sampling bias which occurred when an inadequate number of VINs were used to create the patterns. (To perform the VIN pattern process without small number sampling bias, a very large sample of VIN numbers is required. Condensing a sample of VIN numbers this large is a difficult undertaking.) Another advantage of using a single pool of owners is that it vastly simplifies the recruiting and record keeping process.

Similarly, an additional bias towards better-maintained vehicles may have been caused by the rejection of unregistered or not currently registered vehicles. The rate of vehicle non- or late registrations may be as high as 25 percent, although this rate has never been precisely determined. The actual extent of this bias is not known.

Vehicle Sample Characterization

The distribution of model years for the 332 VSP14 vehicles tested is shown in Figure 1, along with the statewide fleet distribution for comparison. The two distributions match fairly well, although the VSP 14 sample had fewer vehicles less than five years old and more vehicles in the 17 to 19 year old range. (Chi Square tests indicated the differences in these model year distributions were not due to chance and that they were different distributions.) The average age of VSP 14 vehicles was 12.7 years, versus 11.8 years for the statewide fleet.

The VSP 14 vehicles had an average mileage of 119,000 and a median mileage of 112,000 miles. This average is slightly higher than the estimated statewide fleet average mileage of approximately 100,000 to 110,000 miles. The average statewide fleet mileage was estimated from mileage accrual rates compiled from odometer reading changes between Smog Check tests. (The statewide fleet average mileage is not precisely known because this information is not collected by any agency.)

Table 1 provides a comparison of the average mileage and age for the last two VSPs. (VSP 12 and earlier programs did not attempt to capture a full range of vehicle ages, so cannot be directly compared.) It can be seen in this table that the VSP 14 fleet sample was significantly older and with somewhat higher average mileage than LDVSP 13[2]. These changes may reflect how the average age of the statewide fleet has increased in recent years and how new vehicle durability has also increased. These differences should be kept in mind if comparing the results of VSP 14 with LDVSP 13

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[2] Surveillance Programs prior to VSP14 were named "Light-Duty Vehicle Surveillance Programs (LDVSP)," but the Light Duty notation was eliminated starting with VSP 14. References to VSPs in this report include the LDVSPs.

PROGRAM	VSP14	LDVSP13
Average Mileage	119,000	108,000
Average Age (when tested)	12.7	9.7
Program Duration	11/97-8/99	11/95-3/97

Table 1. Average Mileage and Age of LDVSP 13 and VSP 14.

Capture Rate

The capture rate (the rate of participation among those prospective owners contacted) is an important measure of the success of the VSP in obtaining a representative sample. As mentioned previously, a bias can occur if the emissions from vehicles belonging to owners who choose to participate are different than those from similar vehicles belonging to owners who do not[3]. This difference has not been quantified, but it is definitely minimized by maximizing the capture rate. Therefore, obtaining the highest possible capture rate should be an important goal of any VSP program.

The capture rate for VSP 14 was 9.5 percent, calculated by dividing the total number of participants by the total number of people who were mailed letters requesting their participation. This calculation was somewhat conservative because no adjustments were made for mail that was undelivered or not received by the addressee**.** (Rates of undeliverable mail ranged from 30 to 40 percent in the beginning of VSP 14 to about 12 percent after commercial address databases were utilized.) It was also conservative because it included all of the owners contacted for those VIN patterns in the last mailing that were still being pursued at the conclusion of the program. (The last mailing included 20 VIN patterns of which only six were procured, and it is likely more would have been procured given more time.) This calculation also included the owners contacted for the

[3] Preliminary investigation of this question appears to indicate there is a socioeconomic effect on vehicle emissions for vehicles of the same mileage and reported value. This is an issue future VSPs should investigate when the results from the re-designed questionnaire become available.

40 VIN patterns in which no vehicle was procured, such as older, classic, or rarer vehicles with a limited number of owners.

For previous VSPs, capture rates were calculated without taking into account the owners contacted in pursuit of VIN patterns that were never obtained. If these owners were excluded, for comparison's sake, the VSP 14 capture rate was 12.7 percent. Likewise, capture rates for previous programs were: 14.0 percent (LDVSP 13); 15.7 percent (LDVSP 12); 6.1 percent (LDVSP 11); and about 5 percent for previous programs. Thus, VSP 14 is in the range of previous programs, but lower than LDVSPs 12 and 13. Capture rate depends strongly on the motivations of the contractor to contact hard-to-reach owners, the accuracy of the mailing lists (as provided by the DMV), and the particular incentives given to the owner of the vehicle. These have all varied from program to program. Future VSPs should continue to seek improvements in locating current addresses and phone numbers, creating more appealing mailing materials, and experimenting with optimizing incentives.

The major obstacle to obtaining a higher capture rate in VSP 14 continued to be the difficulty in obtaining phone numbers for prospective owners who did not respond to the mailing. (The mailing typically generated a response of 6 to 8 percent.) The fraction of non-participating prospective owners in VSP 14 listed by reason were:

- 60 percent did not have listed phone numbers.
- 15 percent directly refused to participate.
- 12 percent had wrong numbers listed.
- 7 percent had sold their vehicle.
- 3 percent had vehicles no longer in service.
- 2 percent had moved.
- 2 percent could not be reached.

These numbers indicate that the majority of respondents that were reachable had not kept their DMV records current.

The above figures also indicate that, beyond the 6 to 8 percent response to the mailing (most of which were positive), at least 40 percent of the remaining prospective owners refused to participate and at least another 25 percent or more of the prospective owners' vehicles were no longer available. These figures make a capture rate above 30 percent seem unlikely with current VSP resources and incentives. For comparison, similar procurement programs run by CEE with far more generous incentives sometimes only obtain capture rates in the range of 20 percent. Therefore, while VSPs should continue to emphasize improving capture rates, worthwhile gains will likely be measured in single percentage points.

TESTS PERFORMED

Many tests were performed on each vehicle in VSP14. These included simulated I/M procedures, various dynamometer tests, and evaporative tests on selected vehicles. Each of these is described in detail in this section.

The I/M procedures simulated the anticipated Smog Check II tests, which had not yet been implemented at the beginning of this VSP 14 study. The Smog Check II inspection procedures were required in air quality districts not meeting the federal ozone standard ("Enhanced Areas") through December 1, 1997. These procedures included a visual inspection that looked for the presence and correct connection of all relevant emissions control equipment, and a functional inspection which included simple functional tests of the major emission control systems. The visual inspection included checks of the:

- Positive crankcase ventilation (PCV) system.
- Thermostatic air cleaner (TAC).
- Air injection system.
- Fuel evaporation control system.
- Catalyst.
- Exhaust gas recirculation (EGR) system.
- Spark advance.
- Fuel delivery system.
- Oxygen sensors.
- All computer controls.
- Any other emission control systems.

The functional inspections included checks of the PCV, EGR, and ignition systems, the warning and malfunction indicator lights, and the gasoline fill-pipe restrictor size.

Failure of any single component was cause for failure of the entire visual or functional test.

The simulated I/M procedures also included two dynamometer tests, the 5015 and 2525 Accelerated Simulation Mode (ASM) Tests, used in the Smog Check II Program in Enhanced Areas. ASM tests are steady-speed tests set at certain fractions of the load equivalent to that experienced by the vehicle undergoing a 3.3 mph/sec acceleration (the maximum acceleration rate of the EPA's current Federal Test Procedure). The 5015 test is run at 50 percent of this load at 15 mph, and the 2525 is run at 25 percent at 25 mph. A vehicle had to meet emission concentration limits for carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NOx) for both tests. The standards used were internally generated by the ARB based upon linear regression conversion of twice the federal 50,000-mile certification standards. These internal ARB standards were significantly more stringent than those used in the current Smog Check II program. Not meeting the standard for any pollutant for each test was considered a failed ASM test.

The remaining components of the ARB I/M simulation included pressure tests, a gas cap leak test, and a hydrocarbon detector "sniff" test of the vehicle's evaporative control system integrity.

Altogether, these combined I/M simulation tests were used as the criteria for whether a vehicle was considered as "passing" or "failing." Failure of any test was considered cause for vehicle failure. All tests were first performed on each vehicle in its as-received condition. Failing vehicles were then repaired and the process was repeated. The first series of repairs was not to exceed $450 for parts and labor. After repairs, tests were re-run. If the vehicle still failed, repairs were continued from $450 until it was judged no further emissions reductions could be achieved. Figure 2 provides a flow chart of the testing process.

Besides the I/M simulation tests, two other dynamometer tests were conducted as part of the vehicle testing: the CVS (Constant Volume Sampler) Test, which used the EPA's

Federal Test Procedure (FTP) Cycle, and the Unified Cycle (UC) Test. These tests covered a wide range of speeds and accelerations, unlike the single-speed ASMs. The FTP Cycle was designed in the 1970s to simulate urban driving, and the UC was designed in the 1990s to simulate more accurately current urban driving, with higher top speeds, more time at slower speeds, and harder accelerations and decelerations. For comparison, the driving distance for the first two bags of the FTP Cycle was 7.5 miles, 23 minutes in duration, with an average speed of about 20 mph, versus 9.8 miles, 24 minutes, and an average speed of about 25 mph for the first two bags of the UC. The FTP Cycle had a maximum speed of 57 mph and a maximum acceleration of 3.3 mph/second versus a maximum speed of 67 mph and maximum acceleration of 6.9 mph/second for the UC.

Both the CVS and UC Tests collected emissions in a series of three tedlar bags. The first bag collected the cold-start emissions, the second collected the stable-temperature running emissions, and the third collected the hot-start emissions. Unlike the ASM tests, in which only concentrations were measured, the CVS and UC Tests are run with a constant volume sampler that allowed the determination of exhaust volume as well as pollutant concentration. This allowed calculation of mass of pollutant per vehicle mile. (The FTP Cycle Test is referred to as a CVS test because it was the first cycle to use the CVS system.)

Before each CVS or UC test, a vehicle was kept in “cold soak” storage conditions in the temperature range of 68 to 86 °F for 12 to 36 hours. This also differed from the ASM tests, which were run after a vehicle engine was already hot.

The testing process, as illustrated in Figure 2, includes several supplementary tests performed on only selected vehicles. For the evaporative emissions testing, vehicles were chosen if they failed the sniff or pressure tests of the I/M simulation, or else chosen at random. Evaporative tests were referred to as SHED tests, short for “Sealed Housing Evaporative Determination” tests. SHED tests consisted of a 1-hour hot soak and a diurnal test of 24 to 72 hours. The 1-hour test was a hot soak test in which a vehicle hot from a previous dynamometer test was put immediately into the SHED cell (and kept at a temperature of 105 °F) for one hour. The other SHED test was a 1, 2, or 3-day test in which a cold vehicle was kept in a SHED cell while the temperature cycled from 65 to 105 and back to 65 °F in each 24 hour-cycle. In both tests, continuous hydrocarbon concentrations are measured. (Only fourteen SHED Tests were completed in VSP 14 due to other SHED testing priorities during the course of VSP 14.)

Other supplementary tests run in VSP 14 included the Unified Correction Cycle (UCC) tests and "speciated" versions of the CVS, UC, and SHED Tests. UCC Tests were run at various speeds, to determine correction factors for the UC Cycle for different speeds. Speciated Tests involved quantifying organic compounds individually during a test.

RESULTS

I/M Simulation Tests

In VSP 14, 205 of the 332 vehicles tested failed the simulated I/M program, or 62 percent. This agreed fairly well with failure rate of 55 percent found in LDVSP 13. These results were not directly comparable to Smog Check II program failure rates, however, because the ASM standards used by the ARB were more stringent than those used in Smog Check II. As described in the previous section, the ASM standards used were internally generated by the ARB based upon linear regression conversions of twice the federal certification standards, standards that vary by model year groups. (In 1998, only about 10 percent of the vehicles tested in Smog Check II programs for Enhanced Areas failed the Smog Check II standards.)

Broken down by type of failure, 34 percent of VSP 14 failures failed the visual inspection, 41 percent failed the functional inspection, 15 percent failed the gas cap inspection, 16 percent failed the sniff test, and 14 percent failed the pressure test. (The total percentages exceed 100 percent because some vehicles failed more than one inspection or test.) Because the visual and functional tests at the ARB had the same pass/fail criteria as the Smog Check II tests, these results could be directly compared.

For 1998, Enhanced Areas only had about 5 percent functional and 2 percent visual failure rates during Smog Check II inspections. Therefore, a large difference existed between the ARB's simulated I/M program inspection failure rates and those conducted by the Smog Check II program. The reason for this difference was not known.

Rates of Tampering

Emissions control equipment was considered to be "tampered" if any part of the control system or equipment was removed, disconnected, or modified to alter its function. This determination was important for several reasons. First, repair costs of tampered equipment cannot be counted towards specified repair cost limits for vehicles requiring repairs in the Smog Check II Program. Second, because tampered emissions control equipment is not malfunctioning or worn out, the increasing emissions due to tampering should not be considered a natural part of a vehicle's aging.

In VSP 14, about 31 percent of the vehicles were considered to be tampered. This compares with 37 percent from LDVSP 13 and 19 percent in LDVSP 12. About 25 percent of all repairs made were to tampered components. While it was not possible to estimate the effect of tampered emissions control systems on overall emissions, it is obvious that a significant portion of the emissions reductions seen after repairs could be attributed to repairs which should never have been required. (Emissions reductions due to repairs are discussed in a later section.)

ASM Emissions Test Results

Figures 3 through 5 show the average pollutant concentrations by vehicle mileage intervals of 20,000 miles for the first ASM tests performed on each vehicle. The trend of increasing emissions with mileage was readily apparent, increasing approximately linearly with mileage, although this trend did not begin until 30,000 to 50,000 miles.

The irregularity of the interval averages was due to the strong effect of high emitting vehicles on each average. Figure 6 presents the same results as Figure 3, with error bars of one standard deviation, illustrating the occasionally large relative spread of the data for each interval. The 110, 170, 210, and 220+ thousand mileage intervals had large spreads of emission rates and relatively high averages due to the presence of usually only one high emitting vehicle per interval, while these intervals contained 47, 31, 10, and 18 vehicles per interval, respectively. (These high HC concentrations range from 1200 to 2800 ppm.) Test-to-test variability for a given vehicle was insignificant in comparison to the variability between vehicles.

This phenomenon of occasional high emitters makes detailed trend analysis difficult. In general, distributions of vehicle emissions are highly skewed towards higher emissions compared to normal distributions, and cannot consistently be approximated by other types of distributions such as log normal distributions. VSP 14 results were no exception. For this reason, test results were primarily reported in graphical or tabular format, and statistical analysis was limited.

In spite of relatively large vehicle-to-vehicle variability, agreement between the two ASM tests for the same interval average was high, as seen by the close agreement between tests as shown in Figures 3 through 5. Figures 7 through 9 provide scatterplot graphs of the individual data points to directly compare individual results of the two ASM tests. (For ease of viewing, only the first 50 vehicles of VSP 14 are shown, as a sample.) The lines plotted on each graph were Pearson (least squares) linear regression lines. It can be seen that the slope of each regression line was fairly close to 1.0, ranging from 0.86 to 0.98, indicating that either test tended to give results close in value to the other. Likewise, correlation coefficients r ranged from 0.84 to 0.96 (r^2 ranged from 0.71 to 0.93), indicating good general agreement (as opposed to random scatter) of each data point with this regression line. (If the two tests produced identical results, both the slope and the r would equal 1.0.) NOx results appeared to agree best between both tests while the largest scatter was seen for HC. The 5015 test resulted in about 10 percent higher HC and CO concentrations on average than the 2525, as indicated by the slopes of 0.89 and 0.86, although these slopes were sensitive to the data points of the high emitting vehicles. These scatter plots also indicated that high emitting vehicles could usually be identified with either test, with the exceptions of some vehicles which tested significantly higher in

HC concentration in the 2525 test than the 5015 test. As shown in Figure 7, of the 50 data points shown, about five vehicles showed twice the HC concentration for the 2525 test than the 5015. This may have been due to warm-up and/or idling effects, and should be further investigated. In VSP 14, warm up and idling time was not required to be consistent.

CVS and UC Emissions Test Results

Figures 10 and 11 provide the overall emissions test results for HC, CO, and NOx for the CVS and UC tests, both of which were tests utilizing driving cycles containing various speeds and accelerations on a dynamometer. Both tests used a CVS, which allowed calculating mass of emissions per mile, a more valuable measure of a vehicle's emissions than merely the concentrations measured by the ASM tests. Figures 10 and 11 show trends in emissions versus mileage similar to the ASM results, with roughly linear increases in emissions with mileage starting at 30,000 to 50,000 miles, and relatively larger increases in CO and HC emissions above 190,000 miles. Like the ASM results, occasional high emitters contributed to large vehicle-to-vehicle variability and made trends appear irregular.

Figures 12 through 14 show the CVS and UC emissions test results for a single pollutant. These figures show very high correlation between average CVS and UC tests by mileage interval. HC emission averages were almost identical, while the UC test appeared to consistently give slightly higher CO and higher NOx emissions. This was consistent with the UC test being a more dynamic and harder-driving cycle.

Figures 15 through 17 show scatter plot graphs of the CVS versus UC results for a sample of the vehicles, by pollutant. Like the two ASM tests, agreement between the CVS and UC cycles appeared to be high, with slopes near 1.0 and high correlation coefficients. While NOx and CO emissions appeared to average approximately 20 percent and 10 percent higher for the UC than the CVS cycle (based upon the slope of the linear regressions lines), both tests appeared equally useful for the purposes of measuring emissions or identifying high emitters. A detailed comparison of these tests was beyond the scope of this report, however.

CVS and UC Emissions Test Results by Bag

A further advantage of the CVS and UC tests (besides determining actual emissions mass per mile) was the ability to measure and allow comparison of emissions during different vehicle operating conditions. Three bags were collected during each test, the first collecting primarily cold-start emissions, the second collecting hot-stabilized emissions, and the third hot-start emissions. Results of the tests by bag are presented in Figures 18 through 23.

As expected, nearly all interval averages indicated highest emissions in Bag 1, as this bag collected emissions before the catalyst had the opportunity to reach efficient operating temperatures. However, the UC Tests resulted in significantly higher Bag 1 emissions than the CVS Tests. Comparing Bags 2 and 3, which bag was higher depended upon the test and the pollutant. For the CVS Tests, the second bag results were higher than the third bag except for NOx. For the UC Tests, the third bag was always higher than the second. (Because the fraction of the cycle mileage and time collected by each bag was quite different between the CVS and UC cycles, the relative bag results are not expected to coincide between the two tests.) Scatter plots (not presented) comparing individual bags between tests or within tests showed much higher variability than the scatter plot test results shown in Figures 15 through 17, probably indicating widely varying rates of warm-up from vehicle to vehicle.

Emissions by Model Year

Figure 24 presents CVS Test emissions by vehicle model year. Trends were similar to those seen when results are grouped by vehicle mileage. Vehicles could be seen to slowly increase emissions with age until they were six to eight years old, from which time emissions increased relatively more rapidly and irregularly.

Emissions Results Before and After Repairs

As mentioned previously, any vehicle not passing the simulated Smog Check II I/M inspection (visual, functional, fuel cap/pressure/leak check, and ASM tests) was repaired until the I/M inspection criteria were passed. For the ASM standards, the stricter ARB-generated standards were used, but all other pass/fail criteria used were the same as the Smog Check II criteria. (Only about 38 percent of vehicles passed the I/M inspection criteria without needing repairs.) When repaired vehicles passed I/M criteria, they were given a final CVS and UC test.

The average overall emissions for the entire VSP 14 fleet, before and after repairs, and the emissions reductions due to repairs are presented in Table 2:

	HC	**HC**	**HC**	**CO**	**CO**	**CO**	**NOx**	**NOx**	**NOx**
	Before (ppm)	After (ppm)	Reduction (%)	Before (%)	After (%)	Reduction (%)	Before (ppm)	After (ppm)	Reduction (%)
2525	95	45	**52**	0.56	0.28	**50**	600	400	**33**
5015	86	45	**48**	0.57	0.30	**48**	570	360	**37**
	Before (gm/mi)	After (gm/mi)	Reduction (%)	Before (gm/mi)	After (gm/mi)	Reduction (%)	Before (gm/mi)	After (gm/mi)	Reduction (%)
CVS	1.87	1.52	**19**	20.4	14.8	**28**	1.42	1.11	**22**
UC	1.85	1.64	**11**	25.0	20.9	**16**	1.79	1.61	**10**

Table 2. Emissions Before and After Repairs with Percentage Reduction for Entire VSP 14 Fleet.

This table gives some idea of the reductions the Smog Check II Program might achieve if it had a failure rate on the order of 60 percent (what was seen in VSP 14). It is interesting to note the large difference between the reductions seen for the various tests. The ASM 2525 and 5015 tests, which agree closely, show much larger reductions in emissions after repairs than the CVS or UC Tests. This is likely due at least in part because these are the tests for which vehicles are repaired in order to pass. It is also likely that repairing and adjusting vehicles to minimize steady-state emissions does not minimize cold-start and transient driving emissions. This deserves further study. If one assumes the actual “real world" emissions reductions are best reflected with the UC cycle, the emissions reductions expected from repairing a large portion of the fleet are more modest than indicated by the ASM Tests. It should be noted, however, that the means calculated for Table 2 are sensitive to the emissions from high emitters. While emissions reductions from high emitters are as "real world" as those from other vehicles, many of the high emitters had large trade-offs between NOx emission reductions and reductions in CO and HC, so the relative reductions between pollutants should be interpreted with caution.

The same results are presented for the repaired-only vehicles in Table 3:

	HC	**HC**	**HC**	**CO**	**CO**	**CO**	**NOx**	**NOx**	**NOx**
	Before (ppm)	After (ppm)	Reduction (%)	Before (%)	After (%)	Reduction (%)	Before (ppm)	After (ppm)	Reduction (%)
2525	140	43	**69**	0.76	0.23	**69**	850	450	**47**
5015	120	41	**66**	0.71	0.19	**73**	810	400	**50**
	Before (gm/mi)	After (gm/mi)	Reduction (%)	Before (gm/mi)	After (gm/mi)	Reduction (%)	Before (gm/mi)	After (gm/mi)	Reduction (%)
CVS	2.47	1.52	**38**	28.4	16.5	**42**	1.85	1.22	**34**
UC	2.53	1.38	**46**	35.3	23.4	**34**	2.35	1.84	**22**

Table 3. Emissions Before and After Repairs with Percentage Reduction for Repaired Vehicles Only.

Trends are similar to Table 2, except that for repaired vehicles only, larger reductions in HC were seen for the UC Tests than the CVS Tests.

Figures 25 through 27 illustrate the emissions before and after repairs for the repaired-only vehicles, as tested with the CVS test. These results are typical of the other tests, except the ASM test emissions before repairs show a more irregular increase with increasing mileage (as shown in previous graphs) and the UC test results show a smaller change due to repairs. These graphs illustrate that after repairs, a roughly linear increase in emissions with mileage is still present, although the rate of increase is reduced. The increase in absolute difference in emissions due to repairs increases with emissions, but this increase stays fairly constant as a percentage of the before-repair emissions.

When the before and after repair emissions data are plotted against vehicle year, however, an interesting effect is observed, shown in Figures 28 through 30. For all three pollutants, it is only the middle-age vehicles, from roughly 1975 to 1988 which show most of the reduction in emissions, while the newest and oldest show much less change. The reasons for this effect were not known, but should be further investigated. It may be the little change in new vehicles is due to the much higher rate of passing the I/M standards, and the little change in older vehicle may be due to fewer emissions control systems that could be repaired.

Cost and Most Frequent Types of Repairs Necessary

The average cost of repairs for all vehicles in VSP 14 was approximately $150, including labor time at $50 per hour. Average labor time amounted to $100, and the average parts cost was $50. Just under $50 of the $150 average were parts and labor costs to repair parts or systems considered tampered. The average cost per repaired vehicle was $259. This is comparable to the average repaired cost of $213 for VSP 13.

The actual Smog Check II program average vehicle repair cost for calendar year 1998 was $100. But because the Smog Check II Program has a much lower failure rate than did VSP 14 (10 versus 62 percent), the repair cost per *failing* vehicle in the Smog Check II Program was about $1000--much higher than the average repair cost per failed vehicle in VSP 14. An interesting comparison would be to determine which VSP 14 vehicles would have failed the Smog Check II standards and determine this average repair costs for more of a direct comparison, but this was not done.

Table 4 presents the most frequent repairs necessary in VSP 14, covering approximately 70 percent of the repairs performed.

SYSTEM OR PART NEEDING REPAIR	PERCENTAGE OF TOTAL
Ignition Timing (Adjustment)	7.7
EGR Valve	7.5
Miscellaneous Electronics	7.5
Evaporative Emissions Control Vacuum Line	6.6
EGR System Vacuum Line	5.2
Air Induction System Heat Stove	5.1
Gasoline Filler Cap	4.9
Oxygen Sensor	4.9
EGR System (cleaning)	4.0
Carburetor	3.8
Catalyst	3.7
Air Injection System Diverter	2.8
Air Filter	2.4
EGR System Thermal Vacuum Switch	2.4
PCV System Vacuum Hose	2.4
TOTAL	**70.9**

Table 4. Frequencies of Most Common Repairs, VSP 14.

Evaporative Emissions Test Results

Table 5 presents the results of the SHED testing for VSP 14. (Due to a change in priorities, fewer SHED tests were run for this program than usual.) This number of tests is too small to make reliable conclusions about evaporative emissions, especially because the vehicles selected were a mixture of random selections and those failing leak checks. However, one can see large differences in the average evaporative emissions if the vehicles are grouped by summer and winter fuels, which had different vapor pressures, as shown.

Vehicle Number	Model Year	1-Hr Hot Soak (gm/test)	48-Hr Diurnal (gm/test)	Reid Vapor Pressure of Fuel (psi)	Comments
265	84	21	140	NA	Hose leaks, loose clamps
272	90	38	93	10.5	
274	80	11	79	NA	Evap. vac. line misrouted
276	83	17	61	NA	
277	94	31	73	9.1	Failed leak check
278	89	0.30	72	10.1	
Winter Fuel Avg		**20**	**77**	**9.9**	
282	92	0.34	19	NA	
285	84	3.4	NA	6.4	
287	86	0.28	20	7.4	
290	83	6.3	19	6.6	
292	93	0.19	2.6	NA	
297	93	1.0	6.9	6.7	Failed gas cap test
301	88	1.3	4.4	6.7	
306	86	1.8	17	6.5	
Summer Fuel Avg		**1.7**	**13**	**6.7**	

Table 5. Evaporative Emission Test Results, VSP 14.

CONCLUSIONS

Vehicle mileage and age were the most important determinants of vehicle emissions in the VSP 14 testing. Comparisons of the ages of the 332 vehicles tested in VSP 14 to the California fleet showed the VSP 14 vehicles were somewhat older, on average (12.7 years versus 11.8 years) and there were fewer new vehicles, but overall the VSP 14 sample had a similar span of model years and roughly similar distribution of ages as the California fleet.

Vehicle maintenance was probably the next most important determinant of vehicle emissions, after mileage and age, but this was much more difficult to evaluate. As a result, the primary concern about the representativeness of the VSP 14 sample as well as previous VSP samples should be the historically low capture rate. Low capture rates may have resulted in VSP vehicles and owners being different than those vehicles and owners who did not participate. The VSP 14 capture rate was about 10 percent, slightly below the previous two programs. Further study should be made to compare VSP vehicles and their owners to those vehicles and owners who did not participate. (The VSP 14 questionnaire was re-designed to gather information to aid in this evaluation.) An attempt should be made to quantify the variables besides vehicle age and mileage that most strongly affect emissions, and then see if VSP participants differ significantly from Californians in general in these variables. In addition, efforts to improve the capture rate should continue.

Results of the VSP 14 emissions testing program showed very good agreement between the steady-state ASM 5015 and ASM 2525 Tests, and between the variable-speed CVS and the UC Tests, although the 5015 and UC Tests on average showed slightly higher emissions. All tests showed the same basic trend of roughly linear increases in emissions starting at about 30,000 to 50,000 miles, and at 6 to 8 years of age. This rate of increase often worsened above 200,000 miles. Results by bag (cold-start, hot-stabilized, and hot-start) showed much higher emissions for the cold start condition, as expected. The overall average CVS emissions for the VSP sample before repairs was about 1.9 gram per mile hydrocarbons, 20 grams per mile CO, and 1.4 grams per mile NOx.

While test-to-test agreement was seen to be high for the 5015 versus 2525 and CVS versus UC comparisons, vehicle-to-vehicle agreement for the same test and similar vehicle mileage was low. For example, even within the same mileage interval, standard deviations of measurements were often higher than their average. This was largely due to the presence of relatively few high emitters. These high emitters were also responsible for the irregularity of the graphs of average emissions by mileage. High emitters often had emissions 10 times higher than the emissions of other vehicles in their mileage interval.

When the inspection and maintenance procedures of the Smog Check II Program were simulated, a 62 percent failure rate was measured (although the ARB purposefully used tighter ASM emission standards than those currently used in Smog Check II.) However, using identical criteria for the visual and functional inspection portion, VSP 14 measured much higher visual and functional failure rates (34 and 41 percent, respectively) than Smog Check II (5 and 2 percent, respectively). The reason for this difference is not known. Similar to previous VSPs, high rates of tampering were also observed, tampering defined as any part of the emissions control system removed, disconnected, or modified. In VSP 14, 31 percent of the vehicles were considered tampered. Twenty-five percent of the repairs made in VSP 14 were performed to fix tampered control systems or components.

Repairs were made to any VSP 14 not passing the inspection and maintenance criteria. The average cost per repaired vehicle was $259, including labor time at $50 per hour. The average cost per vehicle for all vehicles was $150, higher than the recent Smog Check II average in Enhanced Areas of $100. But due to the much lower failure rate in Smog Check II, the average cost of repairs for failing vehicles in the Smog Check II Program was several times higher than VSP 14.

Repairs reduced emissions of the repaired vehicles by 50 to 70 percent for the ASM Tests, 35 to 40 percent for the CVS Test, and 20 to 50 percent for the UC Test, depending on the pollutant. Generally, reductions were higher for HC and CO than NOx. Average emissions reductions as a fraction of total emissions were roughly constant by vehicle mileage interval. By vehicle model year, however, the greatest reductions were seen for the middle-aged vehicles of model-years 1975 to 1988, or vehicles roughly 10 to 23 years old.